AD-A039 778 OHIO STATE UNIV COLUMBUS DEPT OF WELDING ENGINEERING F/G 13/8
OPTIMIZATION OF PERFORMANCE OF ARC WELDING USING FLUXES IN WELD--ETC(U)
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OPTIMIZATION OF PERFORMANCE OF ARC WELDING USING FLUXES IN WELDED SHIP STRUCTURES FROM HY-100 AND HY-130 KPSI

A Progress Report

for the

Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

under Contract No. N00014-75-C-0666

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High Purity Submerged Arc Welding Fluxes

from

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March 11, 1977

ABSTRACT

The following report summarizes the progress made in the production of experimental high purity submerged arc fluxes for the welding of HY-130 Steels. The initial studies focused on the effects of flux basicity or acidity on weld metal oxygen content. This study indicates that oxygen levels in submerged arc weld metal are substantially reduced when very basic fluxes in the $MgO-Al_2O_3-SiO_2$ system are used. The mechanical properties of the weldments produced with the very basic fluxes were not greatly improved. However, this trend may be attributed to a weld metal silicon content which exceeded 0.40%.

INTRODUCTION

As demand for higher strength steels increases, the search for better and cheaper ways to join these steels increases also. Methods are available for joining the high strength steels that yield tolerable production rates. The shielded metal arc (SMAW) and the gas metal arc welding (GMAW) processes yield controllable weld quality and mechanical properties within specifications but do not have the high deposition rates possible with the submerged arc process.

The shielded metal arc (SMAW) welding process has found wide use in fabrication of high strength steel. The availability of suitable electrodes has made this approach possible. In general SAW has not been as easily applied as either the SMAW or GMAW processes, although considerable construction has been carried out using the submerged (SAW) welding process with suitable fluxes and electrodes.

The fluxes needed to accomplish a broad study of metal/slag reactions are not commercially available and must be fabricated on an experimental basis for testing. These experimental fluxes were formulated with a range in basicity and with low amounts of impurities in the raw materials. The results show promise of being able to limit the oxygen content and increase fabrication rates of the high strength steels.

Submerged Arc Welding and Fluxes

Submerged arc welding (SAW) is described[1] as:

> "An arc welding process wherein coalescence is produced by heating with an electric arc or arcs between a base metal electrode or electrodes and the work. The welding is shielded by a blanket of granular fusible material on the work. Pressure is not used, and filler metal is obtained from the electrode and sometimes from a supplementary welding rod or the flux itself."

The diagram shown in Fig. 1 illustrates a schematic of the submerged arc process. The process is characterized by high deposition rates of the filler material and high travel speeds. Usually the amount of flux melted to produce a weld is approximately the same weight as the electrode which is melted.

Submerged arc welding can minimize the difficulties encountered with shrinkage or distortion. With proper control the process yields excellent weld quality with adequate mechanical properties in the weld metal for many applications.

Submerged arc welding fluxes may be classified as three basic types: prefused, bonded, and agglomerated:

Prefused fluxes are generally produced by melting mixed raw materials in an electric arc furnace. Once a melt is established in the furnace it is then poured onto chill plates or into water (water shotting). In many cases, the prefused product is glassy in apperance but some have a more stony composition. After cooling the flux is crushed, sized,

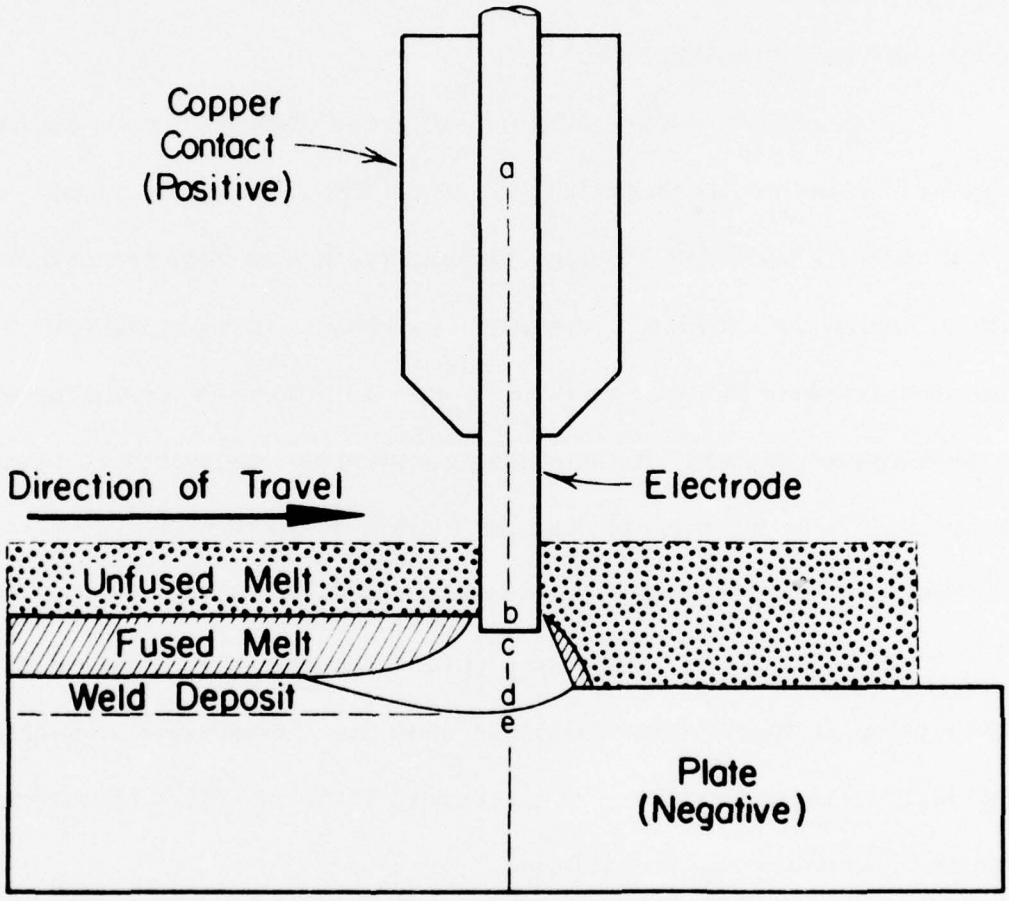

Figure 1 - Schematic of submerged-arc welding process

and then packaged. Prefused fluxes have good chemical homogeneity, and are generally fairly nonhygroscopic; the unused flux may be collected from the weld area and used again since there is little change in particle sizing or composition. The primary disadvantage of prefused fluxes is the inability to add deoxidizers and ferroalloys due to the high temperatures involved in production.

Bonded fluxes are mixtures of ground raw materials bound together by sodium or potassium silicate. This mixture is dried, sized and then packaged. Bonded fluxes have low bonding temperatures which permit the addition of metallic deoxidizers and ferroalloys; the flux is permeable to gases and can be used in thicker layers in the weld zone and generally exhibits good slag removal characteristics. Bonded fluxes tend to be hygroscopic and the molten flux pool may evolve gases. The flux composition may be altered if fines are removed.

Agglomerated fluxes are similar to the bonded fluxes except that a ceramic binder is used instead of sodium or potassium silicate. The high curing temperature of this binder (1400°F, 750°C) limits the use of deoxidizers and ferroalloys.

The determination of a suitable composition for a submerged arc flux depends on many things. Basic theoretical and practical guide lines exist for the formulation of fluxes but final analysis usually depends on actual weld environment testing. The shielding properties of a flux are provided by the molten slag and granular burden. Additions such as TiO_2 are made which improve arc stability while electrical conduction

is usually an inherent characteristic of all molten fluxes. Other additions are made which modify penetration, filler metal melting rates, and the polarity of operation. In order to form the slag which protects the molten metal a slag must be ductile at high temperatures and for ease of cleaning should be brittle at room temperature. The properties of a flux are achieved by carefully choosing and adjusting the melting range of the flux system.

Fluxes also can provide the functions of deoxidation and alloying of weld metal. By use of fluxing agents in the slag, oxides and inclusions in the molten weld pool are removed which improves metal fluidity and increases the quality of the weldment. Oxides are also removed from the weld metal by being reduced by metal deoxidizers such as silicon or manganese. The lime-silica systems are effective in the removal of sulfur and phosphorus compounds from the weld metal. Fluxes that provide alloying elements for the weld puddle contain ferro-alloys and are usually bonded fluxes. Neutral or slightly reducing pre-fused fluxes provide improved recovery of the easily oxidized alloying elements such as chromium, titanium, or columbium.

It is desirable to produce a flux that does not oxidize the alloying elements in the molten weld metal. This is usually achieved by using stable oxides in the flux. These oxides are also an important factor in restricting the formation of non-metallic inclusions in the weld metal. Component oxides which are not stable will result in oxidation of alloying elements and increased percentages of non-metallic inclusions in the

weld metal. Fluxes composed of stable oxides have been shown to improve impact properties.

Submerged arc fluxes may be formulated through the use of theoretical data such as phase diagrams and data on temperature dependent properties. Because of numerous and complex functions required of a welding flux, fine adjustments must be based on actual welding performance. Consequently, compositions in mineral systems with suitable properties for use as submerged arc welding fluxes can be determined only by methodical search of any system. There are however, some guideposts for the initial selection of new oxide systems. A new oxide system must meet the following requirements:

1) The molten flux should form a protective slag.
2) The molten slag should aid in fluxing and deoxidation of the weld metal.
3) The molten metal/slag should control alloying of the weld metal.
4) The flux provides and maintains the environment for the arc.

In commercial production of submerged arc fluxes, natural minerals or production by products are used in the formulation. The final adjustment of welding performance is accomplished by selecting and combining the consituents so that the iron oxide content for example, is held below a specified level. From an economic standpoint deficiencies in welding performance are generally solved by formula additions rather than by refining the components.

Exploratory tests [2] with single components, such as, rutile (TiO_2), talc ($3\ MgO \cdot 4\ SiO_2 \cdot H_2O$), silica ($SiO_2$), magnesia (MgO),

limestone ($CaCO_3$) and others showed a wide variation in the welding performance when used as a submerged arc flux. In the study of various actual rock minerals, promising tests were reported using talc and magnesium bearing minerals as submerged arc fluxes. The performance of a simple material is not adequate for the use as a commercial flux for the SAW process. However, the substitution of MgO for the CaO does provide the possibility of increasing the basicity of the flux since the atomic weight of Mg is considerably lower than that of Ca. The phase diagrams which are available for $MgO\text{-}SiO_2$ [3] indicate that a composition of approximately 35% MgO and 65% SiO_2 provides the lowest melting temperature in the system (Fig. 2). The addition of Al_2O_3 as a third component of this combination provides a ternary system which has shown promise. However, there are certain difficulties in the $MgO\text{-}Al_2O_3\text{-}SiO_2$ system that require further modification. Of the three oxides in this system, SiO_2 is the most easily reduced. Both the MgO and Al_2O_3 are stable oxides in the welding zone. The addition of calcium fluoride to submerged arc flux compositions has been common practice since the early successful compositions were introduced. The fluoride addition has an influence on the electrical performance of the flux composition.

From the tests of single components, talc ($3\,MgO \cdot 4\,SiO_2 \cdot H_2O$) performed in a manner which warrented further study. The melting temperature of the $MgO\text{-}SiO_2$ binary composition could be reduced by the addition of Al_2O_3, CaO or CaF_2 as shown by the available phase

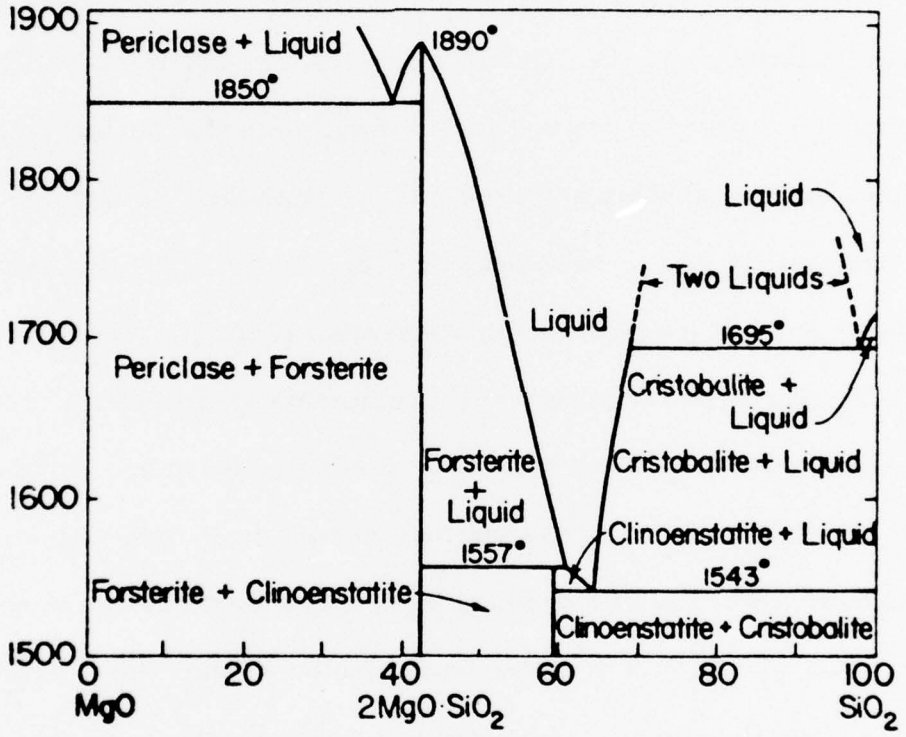

Figure 2 - System $MgO-SiO_2$

diagrams (Fig. [3]). The results of formulation and welding tests showed the most promising compositions in the fused $MgO-Al_2O_3-SiO_2$ system. The addition of alkaline fluorides such as CaF_2 improved the welding performance especially at lower currents. Since MgO provides a convenient control of the basicity of the flux formulation this is a logical system for a more detailed study.

HIGH PURITY SUBMERGED ARC WELDING FLUXES

Many brands and varieties of commercial submerged arc welding fluxes are available today. Most of the commercial fluxes contain trace elements and compounds in the earth raw minerals that are used to make up the flux. The levels of these impurities can vary anywhere from a trace percentage to greater amounts, depending upon the source and grade of the raw material. The complex chemical analysis that is associated with a typical manganese-silicate submerged arc flux is shown in Table 1.[4] These extra elements, or impurities, can be in the form of simple or complex silicates and compounds containing sulfur and phosphorus. These impurities can lead to cracking and low impact values in the weld metal and heat - affected zones unless counteracting steps are taken.

Previous work has shown that submerged arc weld metals have high oxygen contents and many inclusions. Work has been aimed at lowering the oxygen and inclusion contents through the modification of standard commercial fluxes.[5] These studies indicate that CaF_2 and

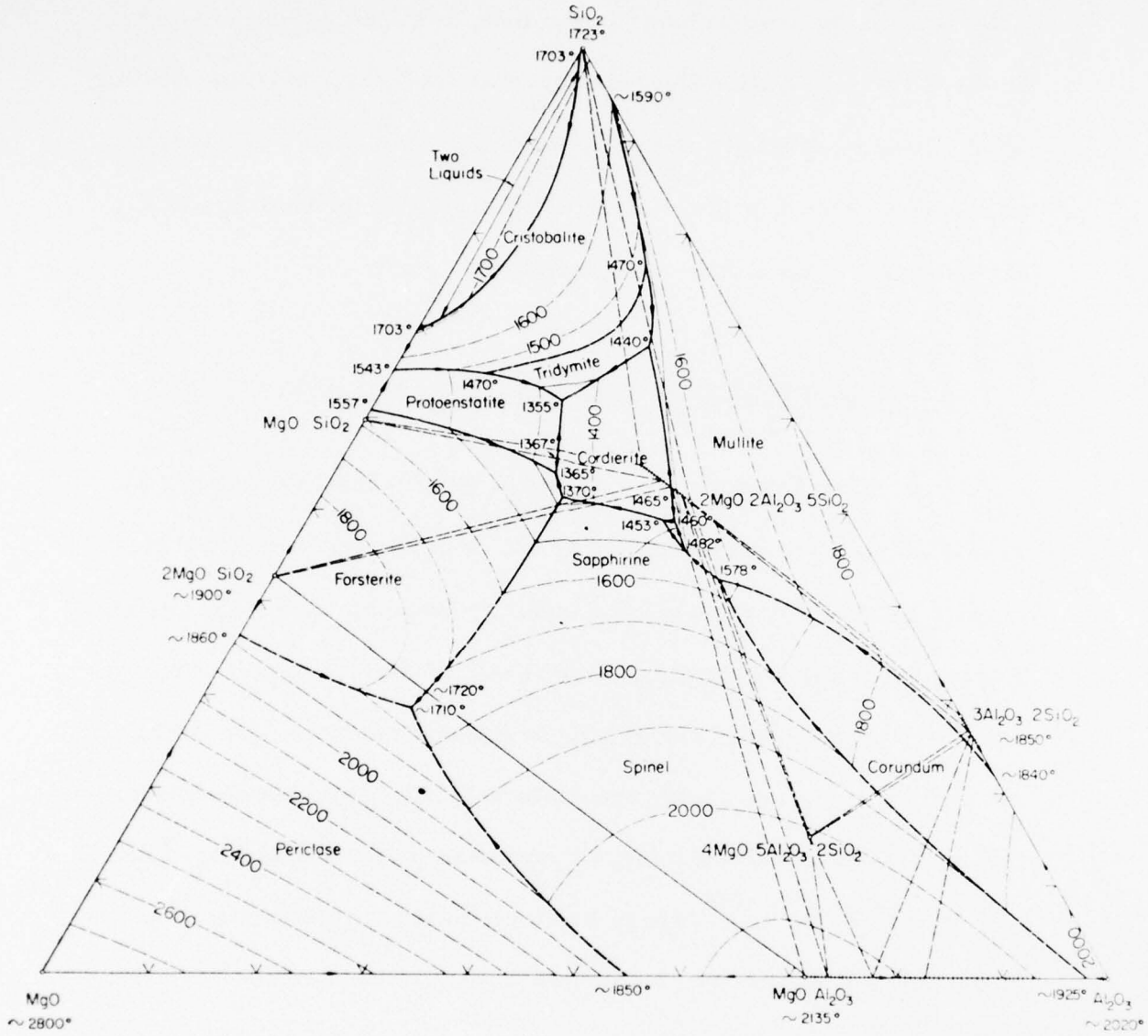

Figure 3 - System $MgO-Al_2O_3-SiO_2$

Table 1. A Comprehensive Chemical Analysis of a $MnO-SiO_2$ Type Flux [4]

Component	per cent
MnO	40.18
SiO_2	46.39
Al_2O_3	3.68
CaO	2.01
FeO	0.90
MgO	0.48
TiO_2	0.16
CaF_2	4.48
Na_2O	0.40
K_2O	0.26
C	0.02
S	0.01
P_2O_5	0.03
PbO	0.05
ZrO_2	0.01
NiO	0.02
V_2O_5	0.05
Cr_2O_3	0.10
CuO	0.30
B_2O_3	Trace
Mo_2O_3	0.10
Total	99.63

TiO_2 were beneficial additions in terms of improving weld-metal notch toughness. The data generated by these studies are not conclusive since the high purity flux was fused in a fire-clay crucible which gave flux-crucible reactions. To avoid this reaction commercial fluxes are fabricated in graphite lined crucibles or hearths where the flux-crucible reactions are kept to a minimum.

Investigations have indicated that the purity of flux and the oxygen and inclusion contents are not the only factors affecting notch-toughness values. There are some indications that changes in weld microstructure due to flux components may also influence notch toughness values.

OBJECTIVES

The object of this research program is the study of the $MgO\text{-}Al_2O_3\text{-}SiO_2$ flux system and its use as a welding flux for high strength steels. Special attention was given to controlling the oxygen content of the weld metal.

Some specific objectives that are being studied are:

1) The survey of basic high purity materials used in SAW flux formulation and their relationship to oxygen content in weld metal.

2) The effect of basic flux formulations on mechanical properties.

PROCEDURES

Submerged Arc Flux

The flux used in these experiments was of two types: commercial and experimental. The following is a list of the commercial fluxes and a typical analysis of them:

Table 2 - Composition of Commercial Fluxes

	Flux A		Flux B	Flux C
CaO	20%	MgO	26%	36%
Al_2O_3	--		22	16
SiO_2	34		16	12
CaF_2	20		22	25
Other	26		14	11

The experimental fluxes used in these experiments were fabricated in tne Welding Engineering facilities at The Ohio State University. A flux development laboratory was constructed during the course of this research. The facilities are now of a permanent nature with excellent ventilation, proper safety equipment, and a moderate degree of automation.

Since previous studies indicate that the $MgO-Al_2O_3-SiO_2$ system could be used as a welding flux, this experimental work was conducted with this system to evaluate its performance on a high strength steel. Experimental compositions were chosen from the $MgO-Al_2O_3-$

SiO_2 ternary diagram (Fig. 3) with appropriate additions as needed to control specific characteristics of the flux. As welding tests were conducted the compositions were adjusted to achieve optimum welding performance.

The fluxes were first prepared in the dry mixed form from raw materials of various degrees of purity. The grade of constituents is indicated by the designations; HP indicating that the ingredients making up the flux were low in residual elements and compounds; and VHP, indicating that the ingredients were as pure a grade as obtainable.

The dry mixed materials were fused in a graphite crucible with internal dimensions of 8 inch deep by 5 inch in diameter. A single one inch diameter carbon electrode was used for melting. The electrode was mounted on a rack and pinion so that the depth of immersion could be adjusted to regulate current. A 450 ampere DC rotating generator welding power supply was used to supply the power to the furnace. Voltage and current were monitored with a Simpson voltmeter and a Simpson millivoltmeter connected across a 600 ampere shunt. Melting time was also monitored. Typical melting characteristics are shown in Table 3.

Melting of the fluxes was initiated by establishing an arc between the electrode and the crucible bottom. Then a portion of the dry-mixed composition was poured in around the electrode. Once a molten puddle was established in the bottom of the crucible the electrode was submerged into the melt and subsequent melting was accomplished

Table 3 - Flux Melting Data

Flux Designation	VHP-II
Heat #	1
Power Supply	Lincoln SAE 400
Meters	Simpson
Shunt	100 mv = 600 amps
Condition of Furnace	Good
Amps, Current	300 amps - DC - electrode negative
Volts	45 volts
Time	30 minutes
Observations	Low viscosity
Flux Color	Gray-white
Flux Appearance	Stony
Quantity Melted	10 #
Power Consumption	0.675 KWH/lb

purely by the resistive heat generated by the current passing though the molten flux.

It was found that there was an optimum depth that the electrode could be immersed into the melt. Immersing the electrode more or less resulted in erratic operation and spattering. The voltage and current were maintained at the level of stable operations and records were made of these parameters. The dry-mixed composition was slowly added to the melt as the melt was stirred with a small graphite rod. When the whole charge was melted the electrode was withdrawn and the furnace was tilted to pour the molten flux onto a chill plate.

After the flux in the chill plate cooled to a level suitable for handling it was broken up and the flux remaining in the crucible chipped out and both were retrieved for crushing. Crushing was done in a jaw crusher and pulverizing was done in a hammer-mill pulverizer. The fluxes were then hand sifted to a 12 x 200 mesh screen size.

The experimental compositions of each of the fluxes was checked for actual analysis by submitting samples to a commercial testing laboratory for chemical analysis (Table 4). These analyses indicated satisfactory agreement of experimental compositions with actual compositions.

Table 4. Flux Composition Before Fusing (As Mixed)

OSU Flux*	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	CaF_2 (%)	TiO_2 (%)	ZrO_2 (%)	$CaCO_3$ (%)	Arc Stabilizer	Flux Basicity***
HP-2	29.1	24.1	17.57	24.7	-	4.24	-	-	1.53
HP-2-2P	29.1	24.1	17.57	24.7	-	4.24	-	1.00	1.55
HP-2-3P	29.1	24.1	17.57	24.7	-	4.24	-	2.00	1.55
HP-2-4P	29.1	24.1	17.57	24.7	-	4.24	-	4.00	1.55
HP-2-5P	29.1	24.1	17.57	24.7	-	4.24	-	8.00	1.55
VHP-I	29.1	24.1	17.5	24.7	-	4.24	-	-	2.05
VHP-I-4P	29.1	24.1	17.5	24.7	-	4.24	-	4.00	2.05
VHP-II	26.3	22.0	16.0	25.0	1.5	4.2	5.0**	-	2.03
VHP-II-4P	26.3	22.0	16.0	25.0	1.5	4.2	5.0**	4.0	2.03
VHP-III	22.3	16.6	36.1	25.0	-	-	-	-	0.93
VHP-1V	36.2	16.6	12.5	28.3	1.0	-	5.4**	-	3.40
VHP-V	27.45	22.96	16.70	26.1	1.57	-	5.2**	-	2.06
VHP-V1	36.6	16.8	12.6	28.6	-	-	5.5**	-	3.59
VHP-V1-A1	38.7	17.8	13.3	30.2	-	-	-	-	3.39
VHP-V11	36.21	17.14	16.64	27.11	-	-	2.90**	-	2.81

* HP = High Purity
VHP = Very High Purity

** Added as a mechanical mix after flux was fused and sized.

*** Flux Basicity = $$\frac{\%MgO/40.3 + 1/2\% Al_2O_3/101.96}{\%SiO_2/60.08 + 1/2\% Al_2O_3/101.96}$$

WELD TESTS

Materials

The experimental work was done using the submerged-arc process with various fluxes. The filler material used was Linde 140 wire with the following composition:

	Percent
Carbon	0.12
Manganese	1.57
Silicon	0.37
Phosphorus	0.006
Sulfur	0.010
Oxygen	0.0016
Nitrogen	0.0042

The plate material used in all of the experiments was HY-130 material with the following typical composition:

HY-130

Element	Percent
Carbon	0.12
Manganese	0.60 - 0.90
Silicon	0.20 - 0.35
Nickel	4.75 - 5.25
Chromium	0.40 - 0.70
Molybdenum	0.30 - 0.65
Vanadium	0.05 - 0.10
Titanium	0.02
Copper	0.025
Phosphorus	0.010
Sulfur	0.010

All of the high strength base material was one inch thick. The plate was oxygen cut utilizing machine equipment. The size and dimensions were as follows:

32 pads 6x4x1 inches HY-130

16 plates 22x8x1 inches HY-130 (long side beveled 22^{o})

8 backing bars 19x3/4x1 HY-130

The heat number of the material is:

HY-130 6B/L-K-3 468-040

The backing bars for weld metal test plates were furnace annealed to ease their removal after welding was completed. All scale and oxidation was removed from the surface of the materials used in experiments. Preparation of the all weld metal test plates is shown in Fig. 4.

Equipment

The base material used in these tests was HY-130. For the chemical analysis pads the small 6x4x1 inch plates were used.

The equipment used for these tests was:

1. Miller SR-1000-A1, Transformer Rectifier, DC Power Supply, 1,000 amp - 100% Duty Cycle.
2. Linde UEC-1 Unionmelt Welding Control and SEH-1 Wire Feeder
3. Linde OM-48 Side Beam Carriage
4. Linde Type C Electronic Governor
5. Esterline Angus Model AW, Strip Chart Recorders
6. Mosely 7005A X-Y Recorder with Hewlett Packard Time Base
7. Resistance Heaters with Thermo Electric Controller

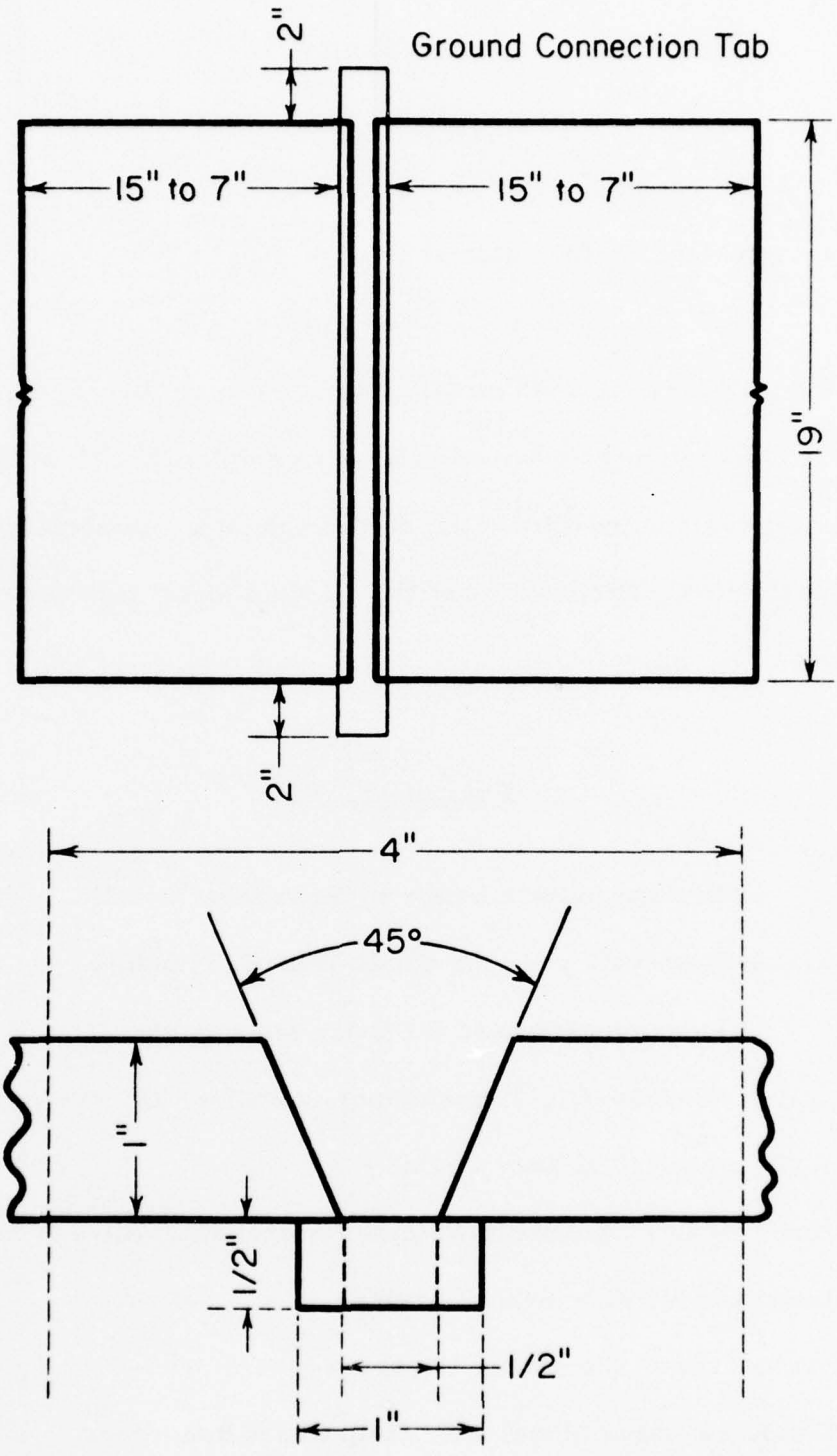

Figure 4 - Joint preparation used for mechanical property plates

Chemical analysis weld pads were prepared and used as a preliminary evaluation of the experimental fluxes. Previous bead-on-plate tests indicated that all of the experimental fluxes performed satisfactorily from a weld appearance and soundness standpoint. The welding variables used in the chemical analysis pad preparations are shown in Table 5. All of the pads were layered as pictured in Fig. 5. In all cases five layers were used and samples taken 1/4 inch below the top surface. After each layer the pad was quenched in water. In some instances slag removal was a problem and when this occurred the shards adhering to the bead deposited were removed with a hand grinder.

After completion the pad was sectioned and sent to a commercial laboratory for analysis. Based on the results of these analyses four experimental fluxes were chosen for futher testing. The primary criterion for selection was weld metal oxygen content.

In order to further evaluate the chosen experimental fluxes and compare them with a commercial grade of flux, studies were conducted to measure the melting rate, deposition rate and cooling rate associated with each flux.

The four fluxes chosen for further study were:

Flux B

OSU HP-2-4P

OSU VHP-II

OSU VHP-II-4P

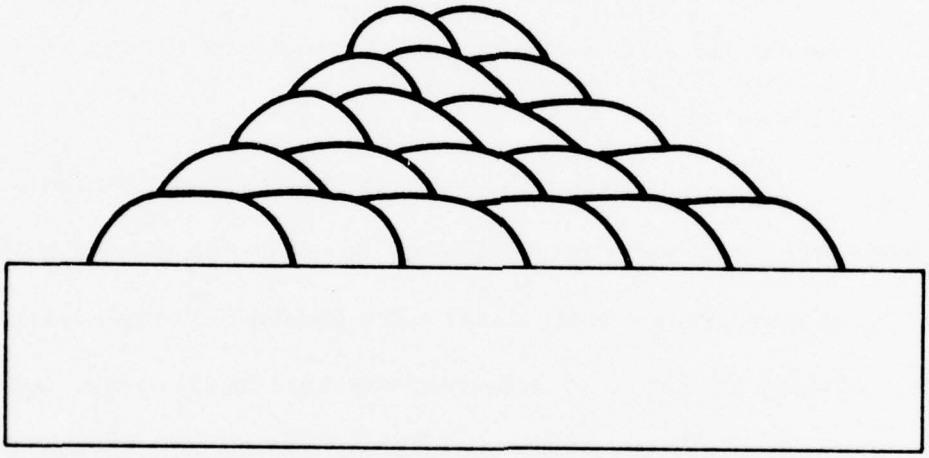

Figure 5 - Weld metal chemical analysis pad for submerged arc fluxes

Table 5. Weld Metal Chemical Analysis Pads, Weld Parameters and Oxygen Content of Weld Metal

Pad Desig.	Flux *	Arc Stabilizer (%)	Current (amps)	Voltage (volts)	Travel (mm/sec)	Flux Basicity	Oxygen Content (ppm)
1S	A	1	400	32	5.29	1.53	292
2S	B	1	400	30	5.18	2.13	218
3S	C	None	385	30	5.29	2.90	194
4S	C	1	400	30	5.29	2.90	200
5S	B	None	400	30	5.29	2.13	217
6S	A	None	400	30	5.29	1.53	320
7S	HP-2	None	400	30	5.29	1.55	313
8S	HP-2-2P	1	400	30	5.29	1.55	287
9S	HP-2-3P	2	400	30	5.29	1.55	358
10S	HP-2-4P	4	400	30	5.29	1.55	262
11S	HP-2-5P	8	400	30	5.29	1.55	322
12S	VHP-I-4P	4	400	30	5.29	2.05	282
13S	VHP-I	None	400	30	5.29	2.05	329
14S	VHP-II	None	400	30	5.29	2.03	260
15S	VHP-IV	None	400	30	5.29	3.40	265
16S	VHP-III	None	400	30	5.29	0.93	623
17S	VHP-V	None	400	30	5.39	2.06	260
19S	VHP-VI	None	400	30	5.29	3.59	153
20S	VHP-II	None	400	30	5.29	2.03	230
21S	VHP-II-4P	4	410	30	5.29	2.03	348
22S	VHP-VI-A1	None	400	31	5.29	3.39	144
24S	VHP-VII	None	400	30	5.29	2.81	174
25S	VHP-VI	None	400	30	5.29	3.59	168

* 1S to 6S commercial fluxes

Three currents were selected for each flux and three separate plates were run at each current. The data associated with these tests are shown in Table 6.

Cooling rate studies were made using the set-up shown in Fig. 6. Cooling rates were measured using platinum versus platinum - 10% rhodium wire 0.020 inches in diameter, and an X-Y recorder. The variables in this study are shown in Table 7. From the beads deposited during the cooling rate analysis, nugget areas were measured and calculated (Table 7). Penetration was measured by using photomacrographs of each bead deposited during the cooling rate studies. Typical polished and etched cross sections of the beads appear in Figures 7 and 8.

Mechanical Property Tests

The test plates used were prepared according to Fig. 4. The filler material was Linde 140, 1/8 inch in diameter. The parameters used in this study are listed in Table 8. All of the plates were preheated to 225° ± 25°F. (106°C.). Interpass temperature was controlled at 225°F (106°C) at all times. The electrode extension was maintained at one inch in all tests.

Forty-eight hours after completing the welding of each plate, the backing bar was removed and radiography was performed to determine weld soundness. As indicated in Table 8, MPS-2 was found to have transverse cracks in the weld metal zone. MPS-5 was then

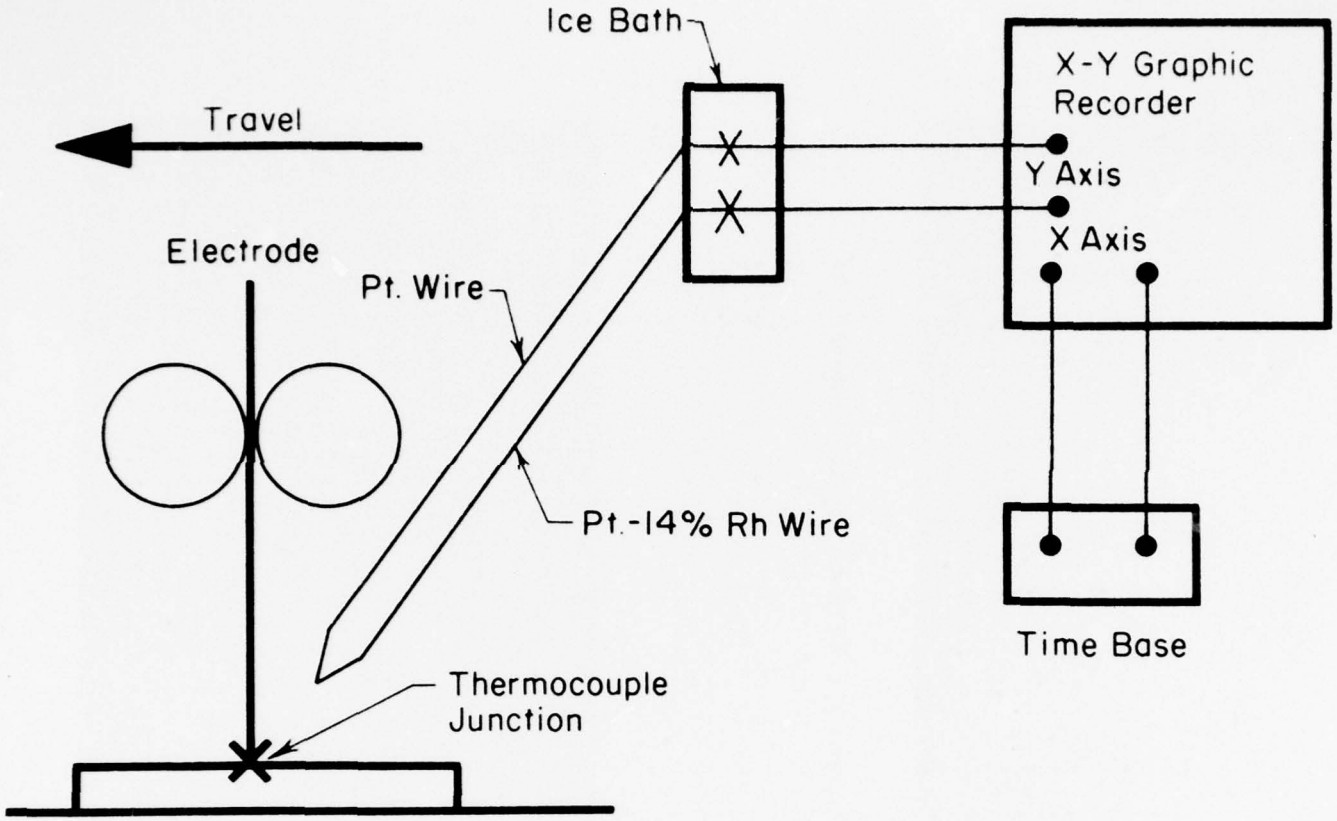

Figure 6 - Equipment layout for measuring cooling rates

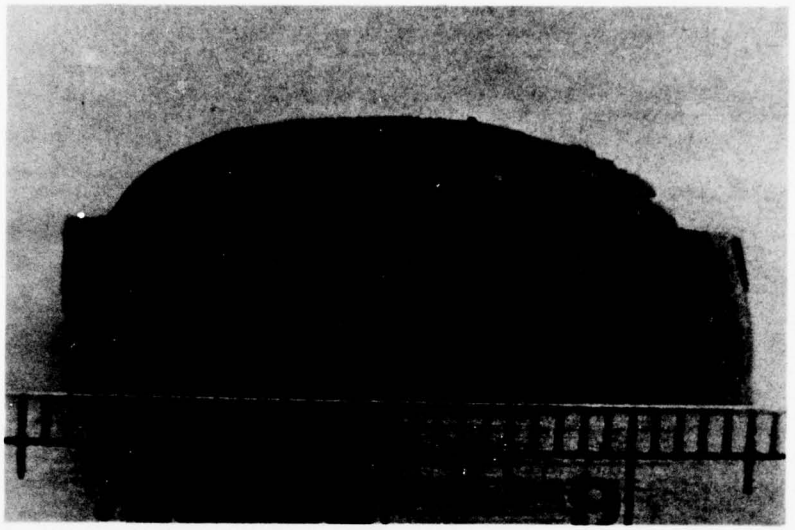

Figure 7 - Bead on "infinite plate", SC-3

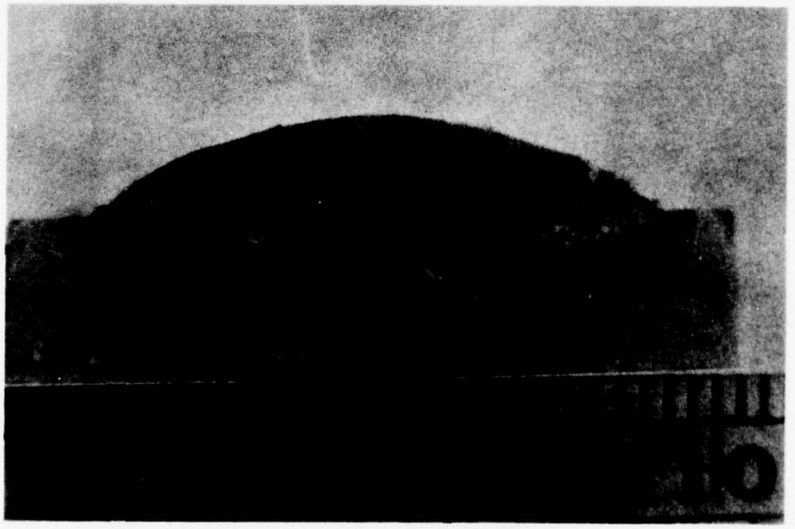

Figure 8 - Bead on "infinite plate", SC-5

Table 6. Test Data for Submerged Arc Flux Characteristics

Plate Desig.	Flux	Current (amps)	Voltage (volts)	Wire Consumed (cm)	Arc Time (sec)	Reen-force-ment (grams)	Slag Weight (grams)	Melting Rate (grams/min.)	Dep. Rate (grams/min.)	Slag/ Weld Metal* Ratio
A	VHP-II-4P	375	30	112.3	34	69.5	82	123.2	122.6	1.17
AA	VHP-II-4P	375	30	110.01	33.9	68.0	85	121.2	120.3	1.25
AAA	VHP-II-4P	275	30	107.9	34.1	70.5	78	118.0	124.0	1.10
B	VHP-II	375	30	112.3	34.9	71.5	69	120.0	120.0	0.96
BB	VHP-II	375	30	112.3	34.8	68.5	74	120.0	117.8	1.08
BBB	BHP-II	375	30	120.9	35.8	75	75	125.9	114.4	1.00
C	Flux C	380	30	107.9	32.8	64	74	122.7	117.1	1.15
CC	Flux C	380	30	117.6	35.4	72	80.5	122.8	122.0	1.11
CCC	Flux C	380	30	116.6	35.0	72	80	124.3	123.4	1.11
D	HP-2-4P	400	30	125.2	38.0	79	78	122.9	124.7	0.98
DD	HP-2-4P	400	30	120.9	35.7	74	76	126.3	124.3	1.02
DDD	HP-2-4P	400	30	120.9	36	78	76	125.3	130	0.97
E	VHP-II-4P	580	30	177.0	34.2	106.3	92	193.1	186.8	0.86
EE	VHP-II-4P	580	30	189.9	36.5	118.5	93	191.2	194.8	0.82
EEE	VHP-II-4P	570	30	181.4	34.7	110.5	102.5	194.9	191.1	0.92
F	VHP-II	573	30	185.7	34.9	115.0	80.5	198.5	197.7	0.70
FF	VHP-II	580	30	211.6	38.9	131.0	94	202.9	202.1	0.71
G	Flux C	595	30	194.3	37.7	122.5	96	192.3	197.5	0.78
GG	Flux C	585	30	181.4	36.5	119	82.5	185.3	195.6	0.69
GGG	Flux C	600	30	194.3	38.7	117	107	187.3	181.4	0.91
H	HP-Z-4P	585	30	181.3	36.2	111	97	186.9	184.0	0.87
HH	HP-Z-4P	585	30	177.0	35.4	111.5	91.5	186.6	189.0	0.82
HHH	HP-Z-4P	585	30	177.0	35.4	111	90.5	186.6	188	0.81

Continued on following page.

Table 6 continued

Plate Desig.	Flux	Current (amps)	Voltage (volts)	Wire Consumed (cm)	Arc Time (sec)	Reen-force-ment (grams)	Slag Weight (grams)	Melting Rate (grams/min.)	Dep. Rate (grams/min.)	Slag/ Weld Metal * Ratio
I	VHP-II-4P	500	30	155.4	34.5	93.5	88.5	168.0	162.6	0.946
II	VHP-II-4P	480	30	151.1	33.9	94.5	86	166.3	167.2	0.91
III	VHP-II-4P	500	30	151.1	33.6	92.5	91.5	167.8	165.2	0.99
J	VHP-II	500	30	181.3	37.8	113	82	178.9	179.4	0.72
JJ	VHP-II	460	30	120.9	33.5	94.7	80	134.6	169.6	0.84
JJJ	VHP-II	500	30	185.6	38.9	113.5	70	178.0	175.1	0.62
K	Flux C	500	30	177.0	38.7	104	99.7	170.6	161.2	0.96
KK	Flux C	500	30	168.4	38.9	103.5	105	161.5	159.6	1.01
KKK	Flux C	500	30	164.0	36.8	97	96	166.3	158.2	0.99
L	HP-2-4P	500	30	168.4	39.1	109	97	160.6	167.2	0.89
LL	HP-2-4P	500	30	177.0	40.9	110.5	100	161.4	162.1	0.90
LLL	HP-2-4P	500	30	168.4	38.3	106	96.5	164.0	166.1	0.91

*Ratio of slag to reenforcement

Table 7. Test Data for Cooling Rate, Nugget Area and Penetration Studies

Bead Desig.	Flux	Current (amps) DC+	Voltage (volts)	Travel (mm/sec)	Cooling Rate (^{o}C/sec)	Nugget Area Cal. (mm^2)	Nugget Area Meas. (mm^2)	Penetration (mm)
SC1	VHP-II	500	25	6.35	*	95.7	121.7	5.01
SC2	VHP-II	500	25	6.35	*	95.7	111.3	5.58
SC3	VHP-II	500	25	6.35	9.07	95.7	132.4	4.16
SC4	VHP-II-4P	550	25	6.35	9.15	110.99	142.4	5.66
SC5	VHP-II-4P	450	28	6.35	7.82	81.32	97.4	3.14
SC6	HP-II-4P	520	26	6.35	10.73	101.7	115.8	4.18
SC7	Flux C	530	27	6.35	8.49	104.8	126.4	3.87

Note: * Cooling rates not taken due to malfunction in X-Y recorder.

Table 8. Welding Parameters for SAW Mechanical Property Plates

Plate Desig.	Mech. Prop. Desig.	Flux	Current (amps)	Voltage (volts)	Travel (mm/sec)	Soundness
MPS-1	S	Flux C	410	30	6.35	Defect Free
MSP-2	-	Flux B	400	31	6.35	Weld Metal Transverse Cracks (See Fig. 12)
MPS-3	T	VHP-II	400	31	6.35	Defect Free
MPS-4	U	VHP-II-4P	400	31	6.35	Defect Free
MPS-5	V	Flux B	410	30	6.35	Defect Free
MPS-6	R	VHP-VI	400	30	6.35	Lack of Fusion at Root in Two Areas 4-5mm Long

welded to duplicate MPS-2 with the exception that the commercial Flux B was baked at 450°F (232.2°C) for four hours prior to welding. Fig. 9 is a copy of a portion of the Xeroradiograph taken of MPS-2. After weld soundness was determined all plates were sectioned; hardness measurements, tensile and yield strength, and Charpy V-notch energies are given in Tables 9 to 11.

DISCUSSION OF RESULTS

The oxygen levels obtained in this experimental work varied from 144 to 623 ppm. Table 5 shows the influence of basicity on the oxygen content. As shown in Figure 10 the more basic fluxes yielded lower oxygen values. Figure 10 also presents data from Hirabayashi[6] et al.

The effect of using high purity fluxes is illustrated in Table 12. The sulfur and oxygen contents in most cases are very low. The silicon levels were higher with the experimental flux pads and in most cases exceeded the level (0.4%) considered to be detrimental to notch toughness of high strength steel weld metal. The melting rates, deposition rates and cooling rates of the experimental fluxes were comparable to those of commercial fluxes, (See Fig. 11)

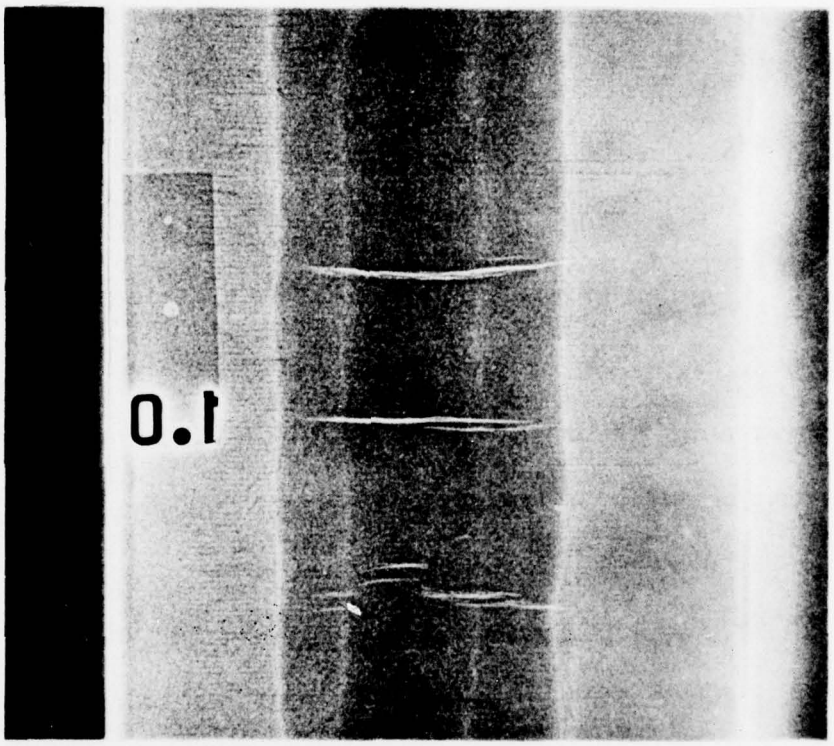

Figure 9 - A portion of Xeroradiograph taken of plate MPS-2 showing weld metal transverse cracks

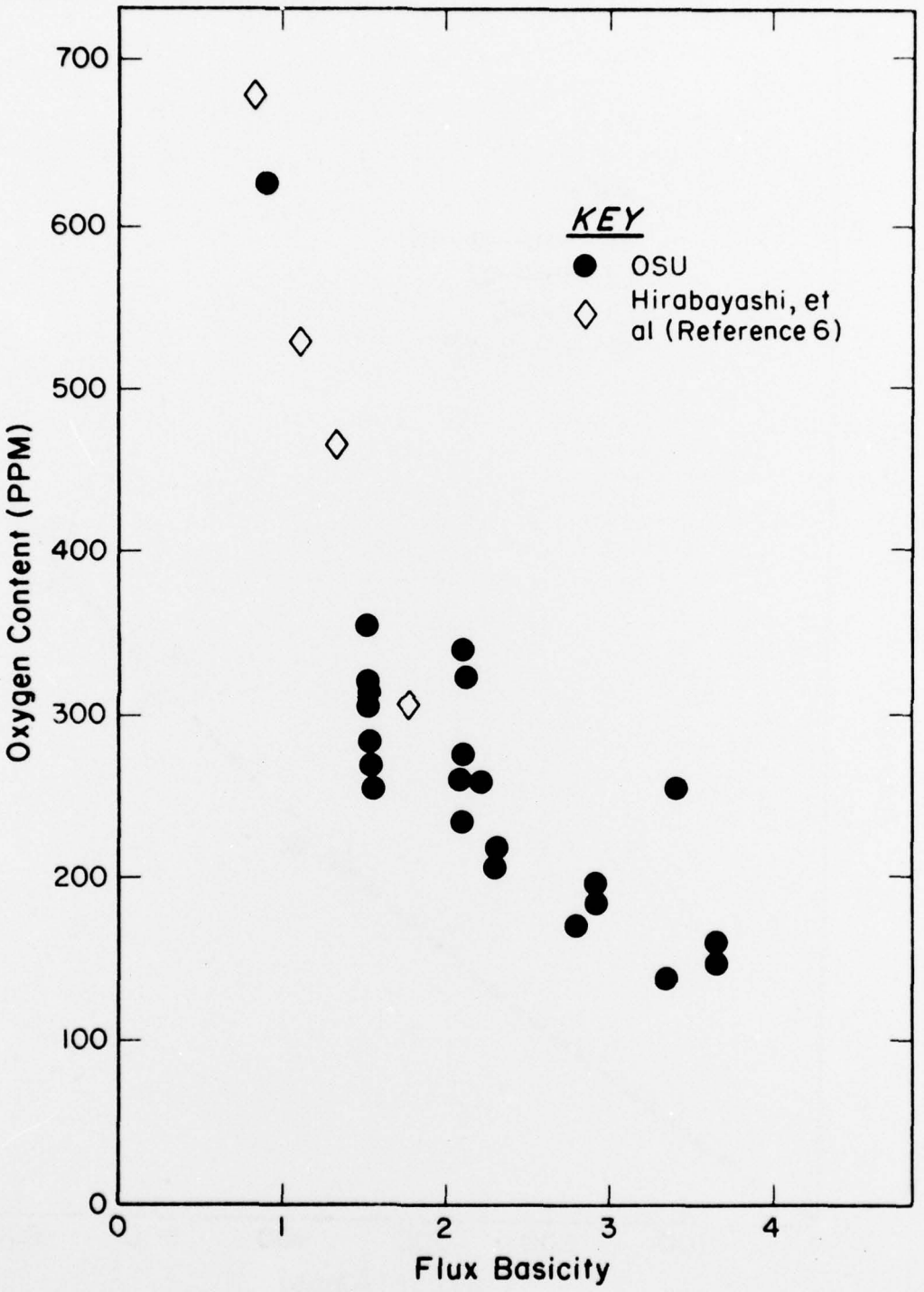

Figure 10 - Oxygen content of weld pads versus flux basicity used in preparation of that pad. (See table 5)

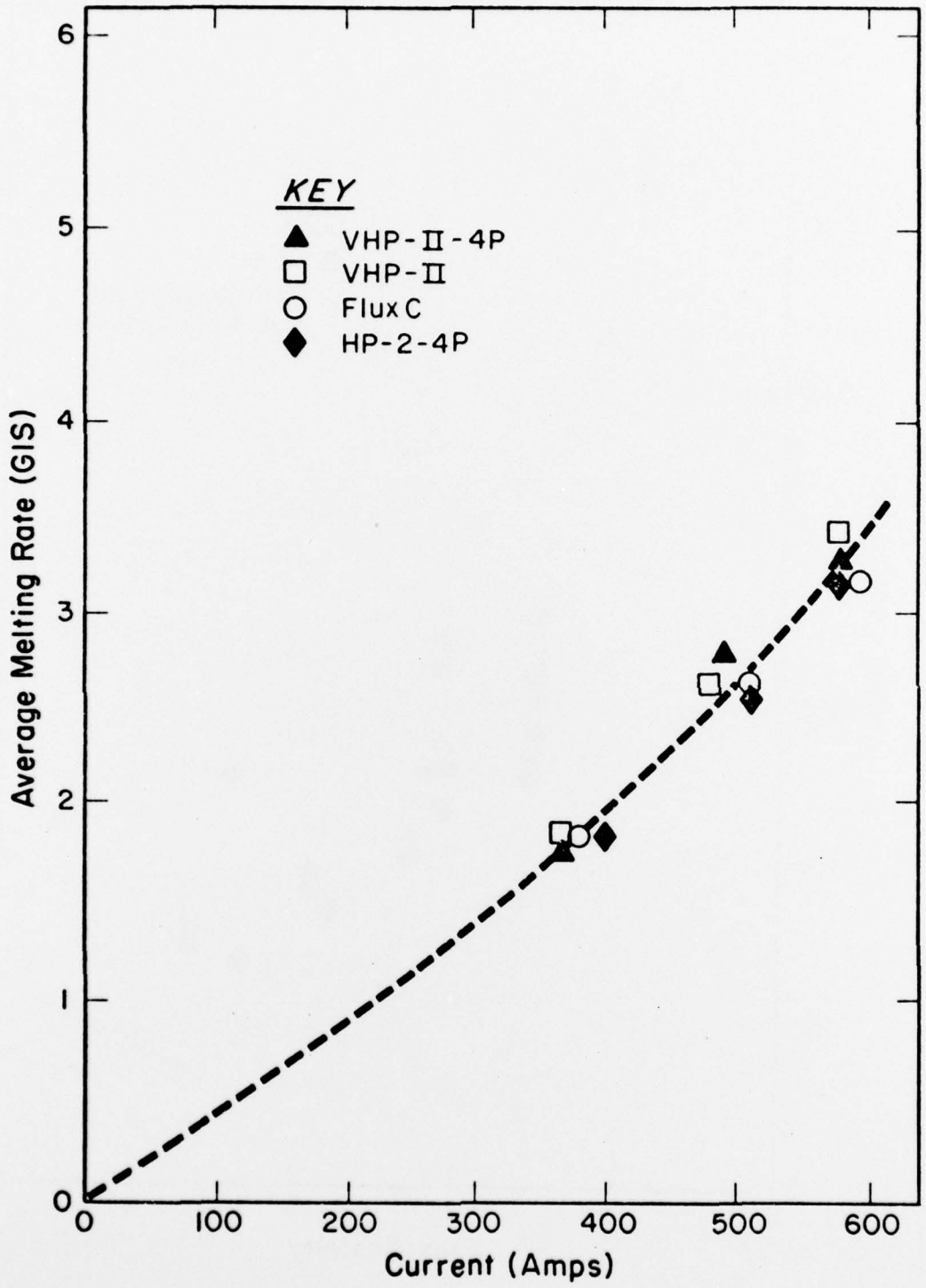

Figure 11 - Average deposition rate versus current for various submerged arc fluxes (DC electrode +)

Table 9. Weld Metal Chemical Analysis (SAW)

Plate Desig.	Sample I. D.	C (%)	Mn (%)	Si (%)	S (%)	P (%)	N (%)	O (%)	Flux Basicity **
MPS-1	S	0.10	1.03	0.19	0.010	0.015	0.0092	0.0232	2.9
MPS-3	T	0.10	1.09	0.48	0.015	0.012	0.0070	0.0262	2.06
MPS-4	U	0.12	1.08	0.54	0.007	0.014	0.0044	0.0128	2.06
MPS-5	V	0.09	1.16	0.33	0.006	0.012	0.0106	0.0221	2.13
MPS-6	R	0.13	1.20	0.48	0.008	0.014	0.0056	0.0149	3.59
MPS-7	*	0.09	1.32	0.54	0.014	0.017	0.0078	0.0146	2.13

* Weld metal transverse cracking experienced, no mechanical properties studied.

** See Table 4

Table 10. Tensile Test Data

Plate Desig.	Specimen I. D.	Flux	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation in 2 in (%)	Reduction in area (%)	BHN (Hardness)
MPS-1	S	Flux C	126.07	138.90	18	58	248
MPS-7	*	Flux B	-	-	-	-	-
MPS-3	T	VHP-II	134.44	149.50	15	44	315
MPS-4	U	VHP-II-4P	139.11	155.34	15	44	346
MPS-5	V	Flux B	131.10	147.96	17	59	315
MPS-6	R	VHP-VI	135.88	155.26	21	59	321

* Weld metal transverse cracking experienced, no mechanical properties studied.

Note: See Table 8 for Weld Parameters.

Table 11. Weld Metal Charpy V-Notch Test Data

Specimen Designation	Test Temperature (°F)	Absorbed Energy (ft-lbs)
R-1	75	43
R-2	0	37
R-3	-20	35
R-4	-60	27
R-5	-80	22
S-1	75	59
S-2	0	52
S-3	-20	51
S-4	-60	35
S-5	-80	29
T-1	75	37
T-2	0	24
T-3	-20	19
T-4	-60	11
T-5	-80	11
U-1	75	32
U-2	0	23
U-3	-20	21
U-4	-60	7
U-5	-80	8
V-1	75	62
V-2	0	43
V-3	-20	47
V-4	-60	32
V-5	-80	20

Table 12. Weld Metal Analysis From Pads

Pad Desig.	C (%)	Mn (%)	Si (%)	S (%)	P (%)	N (%)	O (%)	Flux Basicity
1S	0.10	0.92	0.39	0.011	0.016	-	0.0292	1.53
2S	0.09	1.08	0.30	0.009	0.019	-	0.0218	2.13
3S	0.09	1.18	0.28	0.007	0.018	-	0.0194	2.90
4S	0.09	1.19	0.29	0.008	0.024	-	0.0200	2.90
5S	0.08	1.14	0.33	0.008	0.019	-	0.0217	2.13
6S	0.10	1.00	0.32	0.009	0.025	-	0.0320	1.53
7S	0.08	1.16	0.65	0.010	0.018	-	0.0313	1.55
8S	0.09	1.18	0.68	0.009	0.019	-	0.0287	1.55
9S	0.08	0.87	0.54	0.009	0.016	0.0058	0.0358	1.55
10S	0.11	0.77	0.85	0.009	0.021	0.0061	0.0262	1.55
11S	0.09	0.88	0.63	0.009	0.019	0.0060	0.0322	1.55
12S	0.10	0.95	0.63	0.009	0.011	0.0054	0.0782	2.05
13S	0.09	0.95	0.63	0.010	0.014	0.0059	0.0329	2.05
14S	0.010	0.92	0.50	0.009	0.010	0.0046	0.0260	2.03
15S	0.11	1.00	0.29	0.008	0.016	0.0041	0.0265	3.40
16S	0.05	0.61	1.03	0.010	0.010	0.0112	0.0623	0.93
17S	0.08	1.02	0.58	0.003	0.017	0.0045	0.0260	2.06
18S	0.08	0.74	0.16	0.045	0.062	0.0045	0.0570	2.13
19S	0.14	0.98	0.33	0.002	0.017	0.0055	0.0153	3.59
20S	0.10	1.08	0.58	0.003	0.020	0.0042	0.0231	2.03
21S	0.10	0.95	0.28	0.004	0.023	0.0041	0.0348	2.03
22S	0.18	1.23	1.92	0.011	0.018	0.0049	0.0144	3.39
23S	0.15	1.24	0.31	0.008	0.018	0.0037	0.0174	1.96
24S	0.11	1.21	0.41	0.009	0.018	0.0040	0.0174	2.81
25S	0.13	1.06	0.47	0.011	0.021	0.0040	0.0168	3.59

The weld bead appearance produced by the experimental fluxes was good. At times slag removal was difficult with numerous shards observed. Fluxes VHP-II, VHP-VII and VHP-VI exhibited slag removal difficulties.

The weld metal mechanical properties tests yielded some interesting results. A chemical analysis of the weld metal is shown in Table 9. Table 10 lists values for tensile strength, yield strength, elongation and reduction of area. Table 11 lists values for energy absorbed during impact testing at various temperatures. These results illustrate the detrimental effects of excessive silicon content on notch toughness. A trend of decreasing ductility with increasing basicity was observed. Only the experimental fluxes VHP-II-4P and VHP-VI met the military specifications of 135,000 to 145,000 psi yield strength.

CONCLUSIONS

1. The purity of the raw materials used in these flux compositions does not seem to have a major influence on oxygen content. The $MgO-Al_2O_3-SiO_2$ flux system appears to be a system that can be formulated to yield weld metal with low sulfur, phosphorus, and oxygen levels.

2. The more basic the $MgO-Al_2O_3-SiO_2$ flux system is made, the lower the weld metal levels of oxygen and sulfur. The lowest oxygen level in the weld metal sampled was attained with the

most basic flux.

3. The most basic flux did not yield the best impact properties but an increase to over 0.40% in silicon content in the weld metal is suspected to be a major detrimental factor. The substitution or addition of other oxide components possibly TiO_2 or ZrO_2, for SiO_2 may improve impact properties.

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